PROBING $c \to u\gamma$ IN $B_c \to B_u^* \gamma$ DECAY [a]

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Flavour changing neutral current (FCNC) transitions $c \to u\gamma$ and $c \to ul^+l^-$ are very rare in the standard model and present an interesting probe for the physics beyond it. We study long distance contamination to these short distance processes in different hadron decays. As the most suitable probe for $c \to u\gamma$ transition we propose $B_c \to B_u^*\gamma$ decay. Its detection at the branching ratio well above 10^{-8} would signal new physics. The $c \to ul^+l^-$ transition may be probed at high m_{ll} in $D \to \pi l^+l^-$. The decays $D \to V\gamma$ and $D \to Vl^+l^-$ (V is a light vector meson) are less suitable, since they are dominated by the long distance effects.

1 Introduction

Flavour changing neutral current (FCNC) transitions occur in the standard model only at the loop level, hence they are very rare in the standard model and present a suitable probe for new physics. The rate for the FCNC transition strongly depends on the flavour of the quarks running in the loop: quarks of higher masses give higher rates, as long as their mixing with the external quarks is not highly suppressed. From this aspect the FCNC transitions among down-like quarks d, s and b are relatively frequent: $s \to d$ transitions have been widely studied and recently also the $b \to s$ transition, enhanced due to the large top mass, has been observed by CLEO and ALEPH [1].

The FCNC transitions among the up-like quarks u, c and t are especially rare in the standard model due to the small masses of the intermediate down-like quarks and only the upper experimental limits for this processes are available at present [1]. A possible new heavy state in the loop could greatly enhance the rate of these transitions and they represent a suitable probe for new physics with almost zero background from the standard model. In present paper we explore the $c \to u\gamma$ and $c \to ul^+l^-$ decays, which are the most probable FCNC decays among the up-like quarks in the standard model.

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In practice, the quark decays are probed in hadron decays. A given hadron decay is induced by the corresponding quark decay at short distances (SD), but it is contaminated by the more mundane effects of long distance (LD) dynamics such as the ones induced by propagating intermediate hadrons. We examine SD and LD contributions to different hadron decays within the standard model, proposing the least LD contaminated ones as probes for $c \to u\gamma$ or $c \to ul^+l^-$ transitions or possible new physics. The most suitable probe for $c \to u\gamma$ transition is found to be $B_c \to B_u^*\gamma$ decay [2]; the B_c meson has been detected recently by CDF [3]. Probing $c \to ul^+l^-$ might be possible at high m_{ll} in $D \to \pi l^+l^-$ decay [4] or at low m_{ll} in $B_c \to B_u l^+l^-$ decay.

2 $c \to u\gamma$ and $c \to ul^+l^-$ at short distances

The $c \to u\gamma$ is induced by the penguin diagrams with d, s and b quarks running in the loop, the dominant contribution coming from intermediate d and s quarks (in spite of large m_b the b quark contribution is suppressed due to small $V_{cb}^*V_{ub}$). The amplitude is strongly GIM suppressed at one loop giving the rise to only $BR(c \to u\gamma) \sim 10^{-18}$. Including the QCD corrections at the leading log approximation, the responsible Willson coefficient c_7 (suppressed at one loop) obtains the admixture of the other Willson coefficients (not all of them are suppressed at one loop) and the amplitude is enhanced by two orders of magnitude [5]. The complete two-loop QCD corrections further increase the amplitude by three orders and at this stage the $c \to u\gamma$ is induced by [5]

$$\mathcal{L}_{SD}^{c\to u\gamma} = -\frac{G_F}{\sqrt{2}}\frac{e}{8\pi^2}V_{cs}V_{us}^*c_7(\mu)\bar{u}\sigma^{\mu\nu}[m_c(1+\gamma_5)+m_u(1-\gamma_5)]cF_{\mu\nu}\ , \qquad c_7(m_c) = -0.0068-0.020i \quad (1)$$

giving the rise to $\Gamma(c \to u\gamma)/\Gamma(D^0) \sim 2.5 \times 10^{-8}$. Including further QCD corrections further increase of the rate is not expected [5].

The $c \to ul^+l^-$ is induced by the γ^* and Z penguin diagrams and WW box diagrams, the main contribution again coming form the intermediate d and s quarks. In contrast to $c \to u\gamma$, the $c \to ul^+l^-$ transition is not strongly GIM suppressed at one loop [6]

$$\mathcal{L}_{SD}^{c\to ul^+l^-} = \frac{G_F}{\sqrt{2}}\frac{e^2}{8\pi^2\sin^2\theta_W}c_7\bar{u}\gamma^\mu(1-\gamma_5)c\ \bar{l}\gamma_\mu l\ , \qquad c_7 = -0.065 \quad (2)$$

giving the rate $\Gamma(c \to ul^+l^-)/\Gamma(D^0) \sim 2.9\times 10^{-9}$. QCD corrections to Eq. 2 have not been determined yet, but they are not expected to be sizable.

3 Long distance contributions

In addition to a quark transition at short distances, a given hadron decay is contaminated by LD contributions. We examine different **meson decays** and briefly comment on the baryon decays in the next section. The decays of interest have the flavour content $c\bar{q} \to u\bar{q}\gamma$ and $c\bar{q} \to u\bar{q}\gamma^* \to u\bar{q}l^+l^-$, where $u\bar{q}$ forms a pseudoscalar or a vector meson in the case of l^+l^- and a vector meson in the case of a real photon γ (in this case pseudoscalar is forbidden by gauge invariance). We will choose the flavour of $q = u,\ d,\ s,\ c,\ b$ so that LD contributions will be as small as possible. The emission of the final photon (real or virtual) can proceed *resonantly* via the ρ, ω, ϕ exchange (photon emission from the light quarks) giving the resonant shape in the m_{ll} spectrum or *nonresonantly*.

The most serious is the **LD pole** contamination, which arises via the W exchange in s-channel for the case of $q = d,\ s,\ b$ (sketched in Fig. 1 b) and via W exchange in t-channel for the case of $q = u,\ c$ when in addition a photon is emitted from the initial $c\bar{q}$ or final $u\bar{q}$ meson. The W exchange and corresponding QCD corrections are incorporated in the Lagrangian

$$\mathcal{L}_{LD} = -\frac{G_F}{\sqrt{2}}V_{cq}^*V_{uq}[a_1\bar{q}\gamma^\mu(1-\gamma_5)c\ \bar{u}\gamma_\mu(1-\gamma_5)q + a_2\bar{u}\gamma^\mu(1-\gamma_5)c\ \bar{q}\gamma_\mu(1-\gamma_5)q]\ . \quad (3)$$

The magnitude of pole contribution depends on the flavour $q = d,\ s,\ b$ mainly through $V_{cq}^*V_{uq}$ (see Fig. 1b) giving $|V_{cd}^*V_{ud}| = |V_{cs}^*V_{us}| = 0.22$ for $q = s,\ d$ and $|V_{cb}^*V_{ub}| \sim 0.0002$ for $q = b$. Taking

$q = b$ therefore minimizes the LD effects and the least contaminated meson decay to study $c \to u\gamma$ is $B_c \to B_u\gamma$ decay [2]. In D meson decays ($q = d,\ s,\ u$) on the other hand, the pole contribution turns out to be several orders of magnitude larger then the SD contribution [6,7,8]. Note that for $q = c$ there is no pole contribution, but η_c can decay electromagnetically and the weak decay of interest is completely overshadowed in the experiment.

The second is the **LD vector meson dominance (VMD)** contribution sketched in Fig. 1b. Here the transition $c \to u\bar{d}d(\bar{s}s)$ is induced by the second term in Eq. 3, the intermediate $\bar{d}d$ and $\bar{s}s$ hadronize in the vector mesons ρ^0, ω and ϕ, which finally transverse to a photon. This contribution turns out to be proportional to the flavour $SU(3)$ breaking, so it is smaller than the pole contribution. Note that VMD contribution is present in any decay of interest and it does not depend strongly on the flavour of the quark q, since $\bar{q}$ is merely a spectator (see Fig. 1b).

4 Results

Considering the LD pollution, the $B_c \to B_u^*\gamma$ decay presents the most suitable probe for $c \to u\gamma$ transition. The decay has been studied using the factorization approximation and Isgur-Scora-Grinstein-Wise nonrelativistic constituent quark model [2], which is considered to be reliable for a state B_c composed of two heavy quarks. The predicted SD and LD parts of the branching ratio, shown in Table 1, are of comparable size $\sim 10^{-8}$, which in principle allows to probe the $c \to u\gamma$ transition in $B_c \to B_u^*\gamma$ decay. Experimental detection of $B_c \to B_u^*\gamma$ decay at the branching ratio well above 10^{-8} would clearly indicate a signal for new physics. The measurement of this decay would probe different scenarios of physics beyond the standard model: the non-minimal supersymmetric model [9] and the standard model with four generations [10], for example, predict $Br(c \to u\gamma)$ up to 10^{-5}, which would enhance $Br(B_c \to B_u^*\gamma)$ up to 10^{-6}. Such effects could be detected at LHC [11], where 2.1×10^8 mesons B_c with $p_T(B_c) > 20\ GeV$ will be produced at integrated luminosity 100 fb^{-1}.

Similarly, $c \to ul^+l^-$ will be least contaminated by LD effects in $B_c \to B_u l^+l^-$ decay, but here one has to go to the m_{ll} region bellow the resonances ρ, ω and ϕ.

The D meson decays $D \to V\gamma$ [7,8] and $D \to Vl^+l^-$ [6] (V is a light vector meson) have been studied using the factorization approximation and the model, which combines the heavy quark effective theory and chiral perturbation theory. The predicted SD and LD branching ratios for Cabibbo suppressed FCNC decays are presented Table 1 (for completeness also non FCNC decays are presented). They are completely dominated by LD effects and even huge non-standard effects mentioned above would hardly be visible here. These decays can be therefore used as a controlled laboratory for LD effects, which present an important background to extract $b \to s\gamma(l^+l^-)$ in B decays. The SD (dot-dashed) and LD (solid) differential branching ratios $d\Gamma(D^0 \to \rho^0\mu^+\mu^-)/dm^2_{\mu\mu}\Gamma_D$ are plotted in Fig. 2 and one expects that above the resonance ϕ the LD contribution is reduced. In $D \to \pi l^+l^-$ decays the $m_{ll}^{max} = m_D - m_\pi$ is as high as possible and the region above resonance ϕ, nonexistent in other decays, is dominated by short distance $c \to ul^+l^-$ process [4]. The decays $D \to \pi l^+l^-$ at $m_{ll} > 1.25\ GeV$ therefore present another possibility where $c \to ul^+l^-$ might be investigated in the future [4].

Having exhausted the meson decays, let us comment on the baryon decays. The VMD contribution is present in every decay of interest, while potentially more dangerous W exchange pole contribution is absent in decays of the baryons, where all the valence quarks have the same charge. The least exotic decay to look for $c \to u\gamma$, which is not to contaminated by LD effects, is $\Sigma_c^{++} \to \Delta^{++}\gamma$ ($cuu \to uuu\gamma$), but the strong decay channel $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ completely overshadows the weak decays. We are left only with the more exotic decays $\Xi_{cc}^{++} \to \Sigma_c^{++}\gamma$ and $\Omega_{ccc}^{++} \to \Xi_{cc}^{+}\gamma$ as probes for $c \to u\gamma$.

5 Conclusion

In general it is difficult to observe the $c \to u$ transition. The $c \to u\gamma$ transition can be probed in $B_c \to B_u^*\gamma$ decay and the measurement of its branching ratio well above 10^{-8} would signal new physics. The $c \to ul^+l^-$ transition may be probed at high m_{ll} in $D \to \pi l^+l^-$ decay or at low m_{ll} in $B_c \to B_u l^+l^-$ decay.

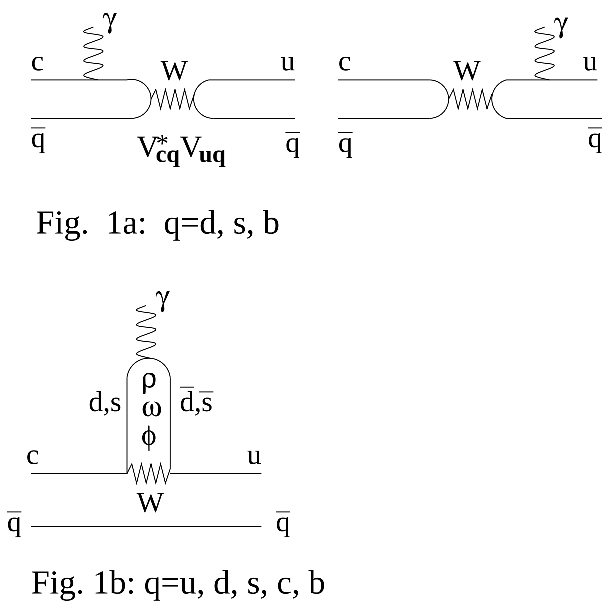

Figure 1: Skeleton diagrams of long distance a) *pole* contribution (photon is emitted from the meson as a whole) and b) *VMD* contribution.

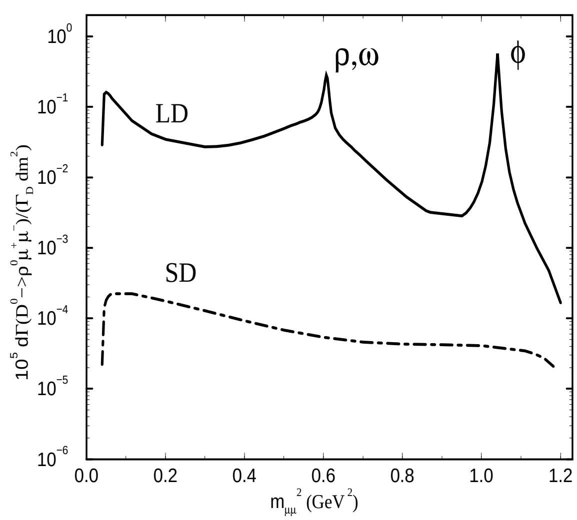

Figure 2: The SD (dot-dashed) and LD (solid) contribtions to $(1/\Gamma_D)d\Gamma(D^0 \to \rho^0\mu^+\mu^-)/dm^2_{\mu\mu}$ as a function of $m^2_{\mu\mu}$ as predicted in [6].

FCNC decay	Br_{SD}	Br_{LD}	non FCNC decay	Br_{LD}
$B_c \to B_u^* \gamma$	4.7×10^{-9} [2]	$7.5(^{+7.7}_{-4.3}) \times 10^{-9}$ [2]		
$D^0 \to \rho^0 \gamma$		$[0.1 - 1.0] \times 10^{-5}$ [7]	$D^0 \to \bar{K}^{*0} \gamma$	$[0.6 - 3.6] \times 10^{-4}$ [7]
$D^0 \to \omega \gamma$	of	$[0.1 - 0.9] \times 10^{-5}$ [7]	$D_s^+ \to \rho^+ \gamma$	$[2.0 - 8.0] \times 10^{-4}$ [7]
$D^0 \to \phi \gamma$	order	$[0.4 - 1.9] \times 10^{-5}$ [7]	$D^+ \to K^{*+} \gamma$	$[0.3 - 4.4] \times 10^{-6}$ [7]
$D^+ \to \rho^+ \gamma$	$10^{-9} - 10^{-8}$	$[0.4 - 6.3] \times 10^{-5}$ [7]	$D^0 \to K^{*0} \gamma$	$[0.3 - 2.0] \times 10^{-6}$ [7]
$D_s^+ \to K^{*+} \gamma$		$[1.2 - 5.1] \times 10^{-5}$ [7]		
$D^0 \to \rho^0 \mu^+ \mu^-$		$[3.5 - 4.7] \times 10^{-7}$ [6]	$D^0 \to \bar{K}^{*0} \mu^+ \mu^-$	$[1.6 - 1.9] \times 10^{-6}$ [6]
$D^0 \to \omega \mu^+ \mu^-$	of	$[3.3 - 4.5] \times 10^{-7}$ [6]	$D_s^+ \to \rho^+ \mu^+ \mu^-$	$[3.0 - 3.3] \times 10^{-5}$ [6]
$D^0 \to \phi \mu^+ \mu^-$	order	$[6.5 - 9.0] \times 10^{-8}$ [6]	$D^+ \to K^{*+} \mu^+ \mu^-$	$[3.1 - 3.7] \times 10^{-8}$ [6]
$D^+ \to \rho^+ \mu^+ \mu^-$	$10^{-10} - 10^{-9}$	$[1.5 - 1.8] \times 10^{-6}$ [6]	$D^0 \to K^{*0} \mu^+ \mu^-$	$[4.4 - 5.1] \times 10^{-9}$ [6]
$D_s^+ \to K^{*+} \mu^+ \mu^-$	[6]	$[5.0 - 7.0] \times 10^{-7}$ [6]		

Table 1: The predicted short distance (SD) and long distance (LD) parts of branching ratio for FCNC decays are presented on the left; non FCNC decays are given on the right. The experimental upper bounds for $Br(D \to V\gamma)$ [12] are at the level 10^{-4}, so this decays might be detected soon. For $Br(D \to Vl^+l^-)$ [1,13] they are at the level $10^{-3} - 10^{-4}$, but there is no existing bound for $D_s^+ \to \rho^+ l^+ l^-$, which has the best chances of detection. The error bars in B_c channel arise form the error in $\Gamma(V^0 \to e^+e^-)$ data used in determination of VMD contribution, which is proportional to flavour SU(3) breaking [2]. In D decays the errors are due to the uncertainty of the parameters in the effective model.

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